

A Simple S-Parameter Test Set for the VNWA2 Vector Network Analyzer

This test set eliminates the need to swap input and output connections to the vector network analyzer when measuring S-parameters.

While beta-testing his VNWA2.1 vector network analyzer, Andreas Zimmermann, DH7AZ, came up with a brilliant idea: He took two RF relays and built a simple switch, which could commutate the VNWA TX and RX ports.¹ Thus, a two port device wouldn't have to be disconnected and turned manually any longer in order to measure its two port S-parameters. Surprising to me, his first veroboard prototype already showed good isolation values. Even more surprising to me, the relay data sheet indicated that at 1.5 GHz, isolations of 60 dB could still be expected.² That's when I decided to build such a switching unit myself, and modify my VNWA software so it would automatically control the relays. This way, the VNWA2 is turned into a full-featured two port network analyzer. The most charming aspect is the simplicity of the circuit, which only requires two relays.

The General Task

Figure 1 shows the general setup of the VNWA2 without S-parameter test set with a two port device under test (DUT). The signal generator's RF passes through a directional coupler into Port 1 of the DUT. The DUT will generally reflect some fraction, b_1 , of the incident wave amplitude, a_1 . The directional coupler or a similar device serves to separate and measure the incident wave amplitude, a_1 , and the reflected wave amplitude, b_1 . The DUT input reflection coefficient S_{11} can be calculated from these measured wave amplitudes, provided that the load impedance, Z_{Load} of the Through Signal detector (RX

Port) is identical to the reference impedance (generally 50Ω) and thus the signal reflected from the detector $a_2 = 0$.

$$S_{11} = \frac{b_1}{a_1} \quad [\text{Eq 1}]$$

The DUT forward transmission coefficient S_{21} can be calculated from the Through Signal, provided that the TX Port impedance is also identical with the reference impedance.

$$S_{21} = \frac{b_2}{a_1} \quad [\text{Eq 2}]$$

Thus, only two of the four DUT S-parameters can be measured with this setup. In order to measure S_{12} and S_{22} , the DUT ports 1 and 2 have to be interchanged manually by disconnecting and reconnecting the DUT. The same effect can be achieved with a simple setup of switching relays, as shown in Figure 2, without manual effort.

S-Parameter Test Set

Figure 2 shows the schematic of the VNWA S-parameter test set. Two relay toggle switches either connect the TX with Port 1 and the RX with Port 2 or alternatively the TX with Port 2 and the RX with Port 1. One interesting aspect of this circuit is the coil driver. The 5 V type relays draw 40 mA each, thus adding up to 80 mA if both relays are to be switched on. Since I wanted to power the test set from the very same USB port as the VNWA, I needed to conserve current. That's why I have connected the coils in series. Once activated, 2 V per relay would be enough to keep them switched on. But a total of 8 V ($2 \times 4 \text{ V}$) are needed to activate both relays. This is achieved by connecting the charged capacitor C4 in series with the 5 V supply.

In the off state (control input low) Q2 is conducting, but Q1 and Q3 are not. C4 is

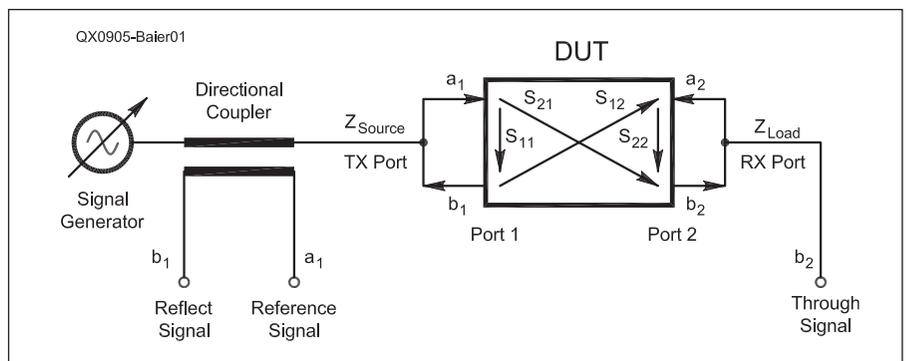


Figure 1 — General setup of the VNWA2 measuring a two port DUT without use of an S-parameter test set.

¹Notes appear on page 32.

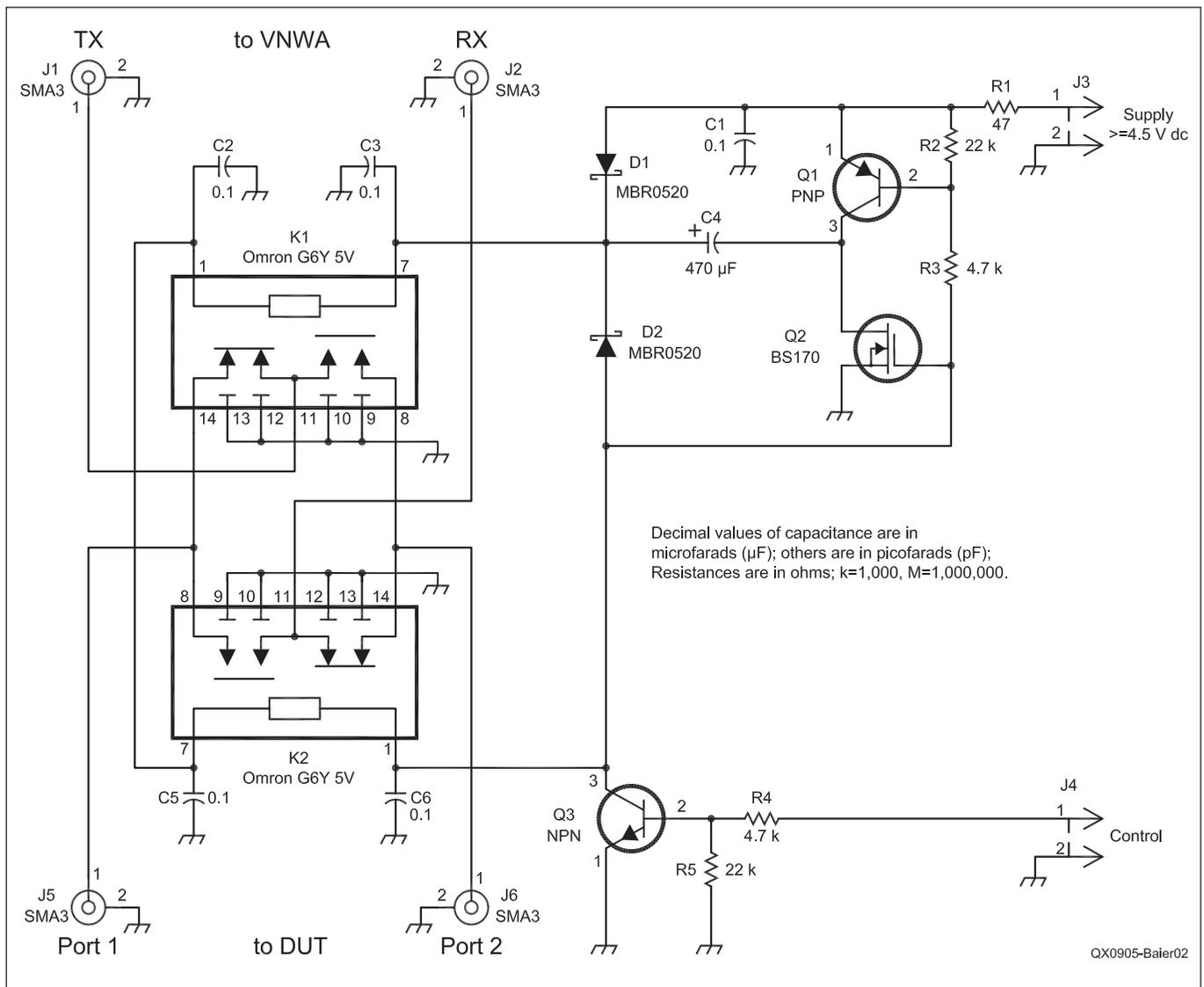


Figure 2 — Schematic of the VNWA S-Parameter Test Set.

charged through D1 and Q2. When the control line goes high, Q1 and Q3 conduct, while Q2 goes into the off state. Q1 connects the minus side of the now charged C4 to the supply voltage, which is thus added to the charge voltage of C4. The sum voltage is enough to activate both relays. After C4 is discharged through the relays, D1 takes over the reduced coil current. A current of 20 mA is enough to hold both relays in the on state. D2 is necessary to suppress high voltage induction voltage spikes, which could damage the driving transistors. I added R1 to further reduce the holding current and as protection: For a very short moment during the activation, Q1 and Q2 are conductive at the same time. R1 serves to limit the current at this moment.

Figure 3 shows the test set from the top. The two black relays can be seen with a shielding wall in between them. The control

signal and the power supply are provided through the 3.5 mm audio connector on the left side. The whole circuit is built up on veroboard, which is covered with adhesive copper foil on the relay side.

Figure 4 shows the test set from the bottom, hooked up to the VNWA2. The driver circuitry is assembled onto the veroboard from the bottom, in surface mount style. In order to achieve the highest possible isolation, the shielding wall protrudes through slots in the veroboard to the bottom, and RF wiring is done with semi rigid coax lines. Also, there is a copper sheet shielding around the relay middle contact pins.

Note, that I have tapped the power supply and the control line at the VNWA control connector, thus avoiding modifications of the VNWA itself. Also note the funny homebrewed biangular male-to-male

adapters, which allow to freely fit different connector spacings by changing the tilt angles.

Figure 5 shows a wideband isolation measurement of the test set from TX to RX port with ports 1 and 2 disconnected. The isolation is only marginally worse than the dynamic range of the VNWA2 up into the GHz range, and is thus sufficient for most two port measurements. Note that 60 dB of isolation is achieved at 1.2 GHz with a single switch, without shunt switches!

Figure 6 shows a wideband transmission measurement of the test set from TX to RX port with ports 1 and 2 connected to each other. The <1 dB maximum insertion loss up to 1.3 GHz can be neglected for the test set application.

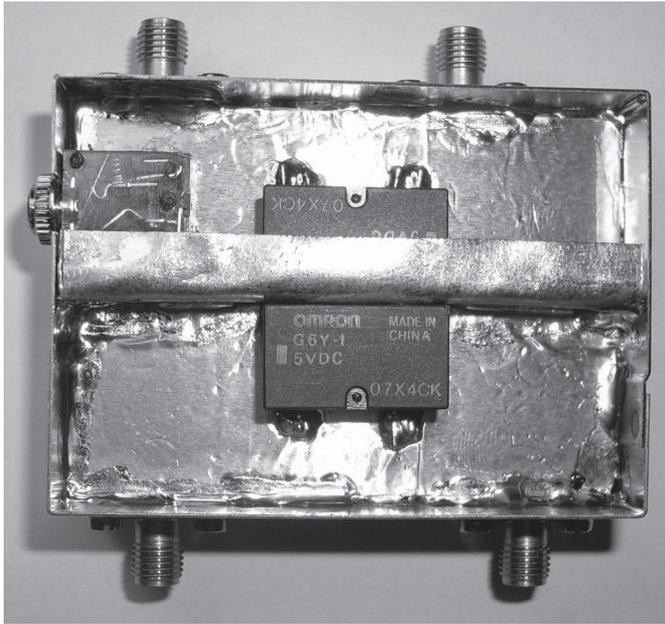


Figure 3 — Test set as seen from top. The shielding wall between the relays is most crucial for good isolation. The sheet metal box size is 65 x 45 mm².

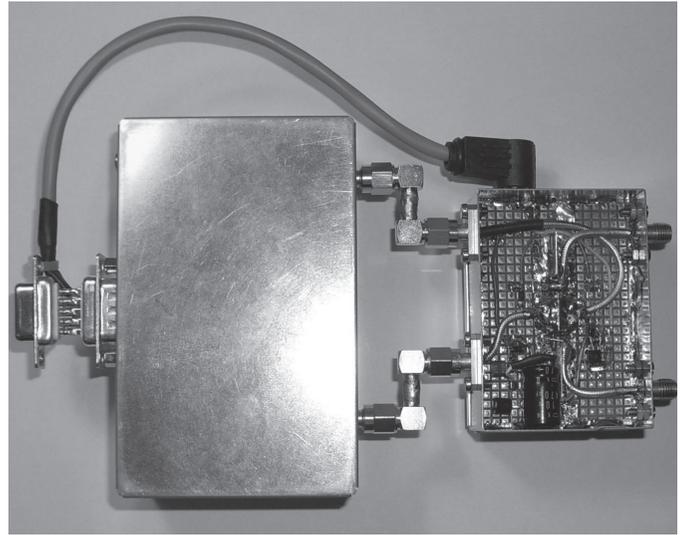


Figure 4 — The test set as seen from the bottom, hooked up to the VNWA2. Note that the connection cable taps the 5 V dc power supply and the control line at the VNWA digital Sub D9 interface.

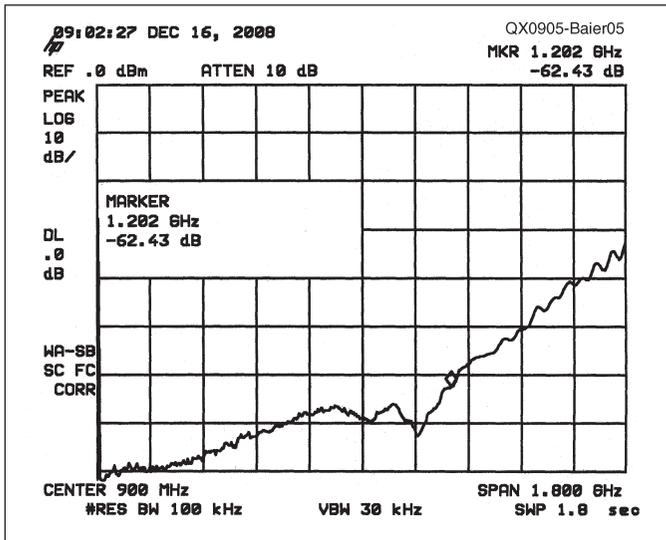


Figure 5 — The isolation measurement of the test set from TX to RX port over 0 to 1.8 GHz with ports 1 and 2 isolated.

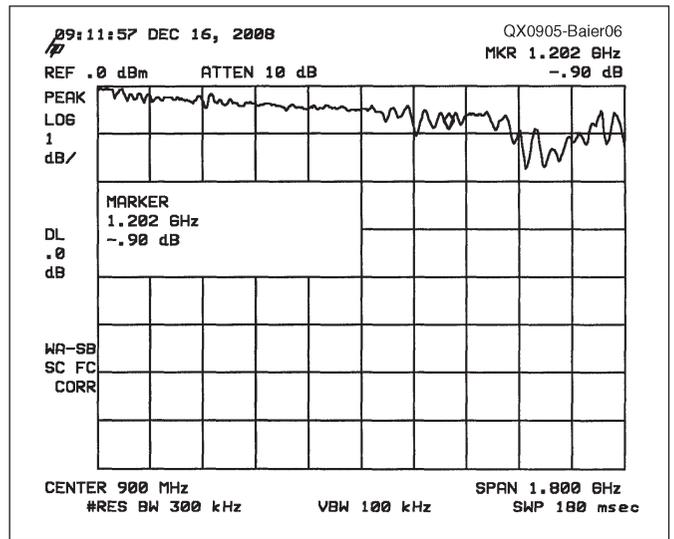


Figure 6 — The transmission measurement of the test set from TX to RX port over 0 to 1.8 GHz with ports 1 and 2 connected to each other.

Advantages of Using a Test Set, Error Correction

The most obvious advantage of the test set is the fact that two port devices can be fully characterized without manually turning them during the measurement. Thus, all four S-parameters (S_{11} , S_{21} , S_{12} , S_{22}) can continuously be measured. This fact yields another, less obvious, advantage: As discussed earlier in this article, S_{11} and S_{21} can be deduced from a forward direction measurement only if the TX port impedance, Z_{Source} , and the RX port impedance Z_{Load} , are both identical to the reference impedance (usually 50 Ω).

If this is not the case, some of the transmitted signal, b_2 , is reflected at the RX port, is retransmitted through the DUT and adds to the reflected input signal, b_1 , which in turn gets reflected at the TX port *again*. Thus, in this case the results of the forward measurement are influenced by all four DUT S-parameters as signals travel through the DUT in both directions. The same holds true for the measurement in the reverse direction. If both directions are continuously measured, then the effects of non ideal source and load impedances can be mathematically corrected in an exact manner. This technique is known

as 12-term error correction.³

Figure 7 shows the measured S_{11} and S_{22} of the through calibration standard. By definition, both reflection coefficients of the through standard are zero. Traces S_{11} and S_{22} show simply corrected results, which are identical with the detector reflection coefficient caused by $Z_{Load} \neq 50 \Omega$. Note that the detector match is better than 25 dB over the displayed span, which is quite good. Mem1 and Mem2 show the same data 12-term corrected. The effect of imperfect load match has completely vanished and the measured data is dominated by noise. The rising noise

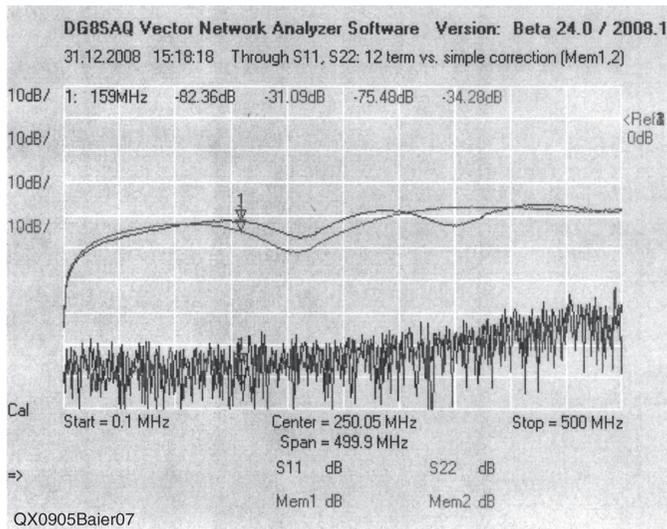


Figure 7 — Impact of 12-term error correction on measured S_{11} and S_{22} of the through calibration standard. Traces S_{11} and S_{22} show simply corrected results, while Mem1 and Mem2 show the same data 12-term corrected.

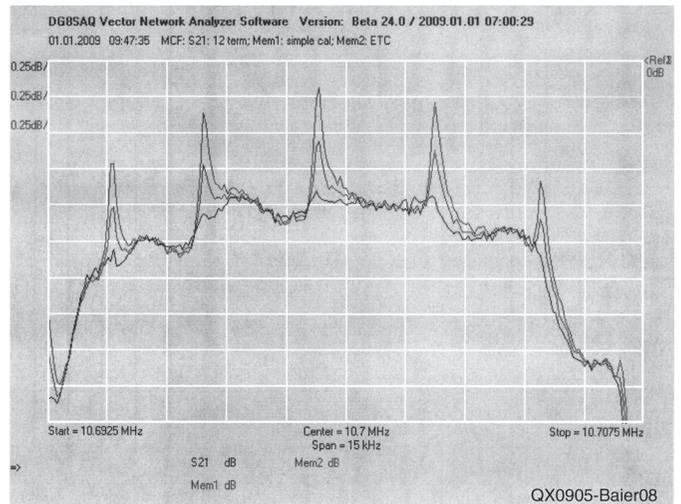


Figure 8 — Transmission data of a monolithic crystal filter measured at a reference impedance of 50Ω with various error correction schemes and then recalculated to source and load impedances of 3000Ω .

floor to the high frequency side reflects the decreasing available signal strength of the instrument.

One should think that the effects of 12-term correction are generally small, but they can become large if the measured S-parameters are used in a system simulation. Figure 8 shows transmission data of a monolithic crystal filter measured with the VNWA at a reference impedance of 50Ω with various error correction schemes and then recalculated to source and load impedances of 3000Ω , which are the optimum filter matching conditions for a flat pass band.

Note that the simple error correction scheme (trace S_{21}) shows distinct spikes in the filter pass band, while the 12-term corrected result (Mem4) is as smooth as can be. Also shown are two simple enhanced through correction schemes (Traces Mem1: ETC1; Mem2: ETC2), which only require measurements in one direction. They partly take into account non perfect matching conditions, but they do neglect multiple reflections. ETC2 can be obtained from the 12-term equations by setting $S_{22} = 0$ for the forward terms and $S_{11} = 0$ for the backward terms. ETC1 is obtained from ETC2 by setting the detector impedance equal to the reference impedance (usually 50Ω). The ETC corrections are better than the simple one, but worse than the 12-term correction.

Summary and outlook

I have described an easy to build automatic 2 port S-parameter test for the VNWA2. In spite of its simplicity, it offers sufficiently high isolation and low insertion loss. The test set also allows application of the very accurate 12-term error correction scheme in a very simple manner. With a little imagination, the test set can easily be upgraded to include bias tee networks for measuring active components. The most recent VNWA software is capable of automatically controlling the test set. It can be found at my Web site.⁴ The version of the VNWA software current as of the publication date of this article is also available for download from the ARRL QEX Web site.⁵

Thanks to Andreas Zimmermann, DH7AZ, for sharing his great test set idea and to Paul Kiciak for many fruitful discussions on error correction.

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Tom, DG8SAQ, has been a licensed radio amateur since 1980. He prefers the soldering

iron to the microphone, though. His interests span from microwave technology to microcontrollers. Lately, he has started Windows programming with Delphi. Tom spent one year in Oregon USA rock climbing and working on his master's degree.

Notes

- ¹Professor Dr. Thomas C. Baier, DG8SAQ, "A Small, Simple, USB-Powered Vector Network Analyzer Covering 1 kHz to 1.3 GHz," QEX, Jan/Feb 2009, ARRL, pp 32 – 36. See also www.arrrl.org/qex/2009/01/Baier.pdf
- ²Omron G6Y Relay, see www.omron.com/ecb/products/pdf/en-g6y.pdf
- ³See, for example, Agilent AN 1287-3, "Applying Error Correction to Network Analyzer Measurements," Application Note, <http://cp.literature.agilent.com/litweb/pdf/5965-7709E.pdf>
- ⁴See www.mydarc.de/DG8SAQ/NWA.html
- ⁵The VNWA software current as of the publication date of this article is available for download from the ARRL QEX Web site. Go to www.arrrl.org/qexfiles and look for the file 5x09_Baier.zip.

